Advanced 3-D LTCC System-on-Package (SOP) Architectures for Highly Integrated Millimeter-Wave Wireless Systems

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***Abstract* - This paper reviews the development of advanced 3-D LTCC system-on-package architectures for compact, low cost wireless front-ends to be used in RF and millimeter-wave frequency ranges. Compact and easy-to-design passive circuits, such as filters and antennas, have hereby demonstrated great performance and high integration potential. The excellent performance of one patch resonator filter is verified through an insertion loss lower than 2.3 dB, a return loss larger than 18.2 dB over pass band, and a bandwidth about 6.4%. Also, experimental results of one directional filter show insertion loss of <3dB over the band pass section and a rejection ~ 25dB at around 38.5GHz over the band rejection section. LTCC design limitations have been overcome by using vertical coupling mechanisms to satisfy millimetre-wave design requirements. In addition, a double fed cross-shaped microstrip antenna has been designed for the purpose of doubling the data throughput by means of a dual-polarized wireless channel, covering the band between 59-64 GHz. This antenna can be easily integrated into a wireless millimeter-wave link system.**

I. INTRODUCTION

Millimeter-wave (mmW) electronics for commercial applications, such as short-range broadband wireless communications and automotive collision avoidance radars, require low-manufacturing cost, excellent performance, and high level of integration. The multilayer LTCC System-On-Package (SOP) approach is very well suited for these requirements, because it offers a great potential for passives' integration and enables microwave devices to be fabricated with high reliability, while maintaining a relatively low cost [1]. In this paper, we present the development of various advanced 3-D LTCC system-on-package architectures enabling a complete passive solution for compact, low cost wireless front-ends to be used in RF and mmW frequency ranges. The 3D embedded functions, which have been developed, include slotted patch resonator filters for achieving compactness and great compromise between size and power handling, and directional filters to provide easy and compact solutions for applications, such as mixing and multiplexing. A cross-shaped antenna has been designed for a dual-polarized transmission and reception of signals that cover the band between 59-64 GHz, and can be easily integrated into a wireless mmW module. This demonstration is a strong indication that LTCC system-on-package approach can emerge as one of the most effective solutions for the flexible and reconfigurable systems required in the growing number of mmW applications.

II. 40 GHZ PATCH RESONATOR BAND PASS FILTER (BPF)

One important function that can be easily integrated in multilayer modules is filtering. In order to maintain their properties in compact topologies, band pass filters are commonly realized using slotted patch resonators in mmW frequencies due to their miniaturized size, the great compromise between size and power handling and their easy-to-design layout [2]. In this paper, one single pole slotted patch filter with a transverse cut on each side has been designed and embedded in LTCC (ε_r=5.4, tanδ=0.0015) for 38-40GHz applications such as remote sensing and secure communications. The top view of the patch filter (1.02 mm×1.02 mm) designed for a 6.5% bandwidth, 39 GHz center frequency, and <3dB insertion loss, is shown in fig 1 a. Such a structure has been developed from the basic half-wavelength square patch at 39 GHz by adding a transverse cut (L_c) on each side. Transverse cuts (L_{cw}=L/8, L_{cl}=L/3) contribute to significant additional inductance so that the operating frequency range is shifted about 38%. Therefore, the patch size is reduced significantly and also the widely-spread current distribution allows for an effective power handling. The degradation of bandwidth due to the patch's miniaturization can be improved by adjusting the overlap distance (L_{over} in fig. 1 a)) between resonator and feed lines that directly affects the external quality factor (Q_{ext}). The desired coupling coefficients are obtained by placing the feed lines and the resonator into different vertical metal layers as shown in fig 1b. The insertion loss of the filter can also be evaluated as a function of the overlap distance (L_{over} in fig. 1a) between the resonator and the feed lines. The stripline filters are excited through vias connecting the top metal with the next underlying metal (fig.1b), enabling the package to prevent radiation loss [2]. The experimental results of the filter agree very well with the simulation data as shown in fig.1c. It is revealed that the insertion loss is < 2.3 dB, the return loss >18.2 dB over pass band, and the bandwidth is about 6.4%. The shift between the measured and the simulated center frequencies can be attributed to the pad/probing effect and to the fact that the fabricated patch is slightly oversized.

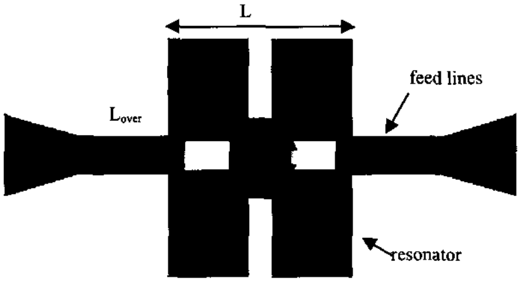

Fig.1 a) Top view of V band patch resonator BPF

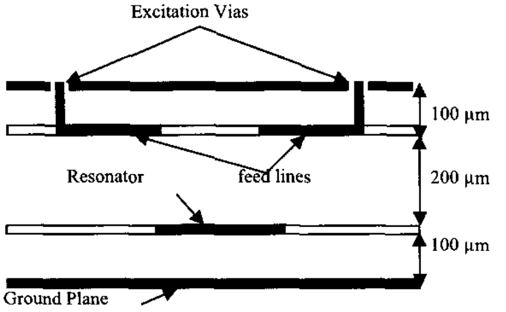

Fig. 1 b) Side view of V band patch resonator BPF

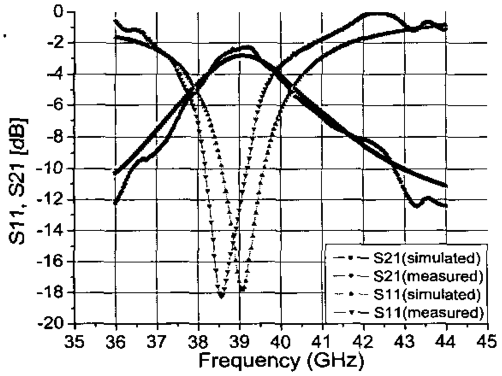

Fig. 1 c) Measured and simulated S-parameters of patch resonator BPF

III. 40GHz DIRECTIONAL FILTER

This paragraph presents one 40GHz 4-port directional filter with excellent performance in LTCC technology. As shown, in fig 2a, the device exhibits a band-rejection characteristic between ports 1 and 2, and a band-pass characteristic between ports 1 and 4. The other port (#3) is isolated from the input (port1). [3] The integrated structure is symmetric. It can be used in mixer applications to mix RF and LO signals with high isolation between them. Several directional filters can be cascaded to achieve frequency multiplexing as well as demultiplexing due to the frequency selective nature of one output along with rejection at the other output. Simple and compact implementation has been achieved using microstrip lines with reduced number of metal layers as compared to striplines. The band-pass section shows an insertion loss of <3dB and the band-reject section demonstrates a rejection value of ~25dB at around 38.5GHz. The high quality factor of the ring resonator assures the narrowband operation and, hence, this topology can be used efficiently in frequency selective applications. In this single loop directional filter, the coupling between the ring resonator and the transmission lines has been achieved by vertically coupled structures alleviating the need of a very narrow broadside (horizontal) coupling distance, which could not be realized in LTCC. The effective lengths of all sides of the ring have been made equal to one quarter of the wavelength. The 50Ω impedance level is preserved throughout the complete circumference of the loop by optimizing the width of the sides of the ring for both coupled and uncoupled sides. At the working frequency band, the signal couples from the input transmission line to the embedded ring and hence the required band-pass and band-reject characteristics are achieved (fig.2a). The dielectric thickness is 100um between the metal layers and it occupies an area of 2mmx2mm. The layout and the performance of the filter are shown in figs.2b,c respectively.

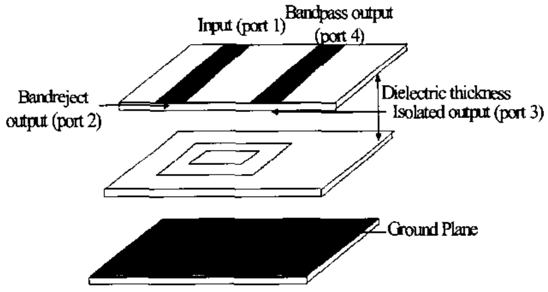

Fig. 2 a) Implementation of the directional filter in multilayer LTCC substrate

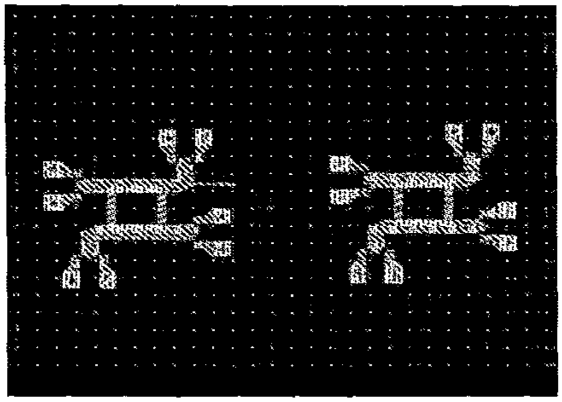

Fig.2 b) Layout of the 40GHz directional filters

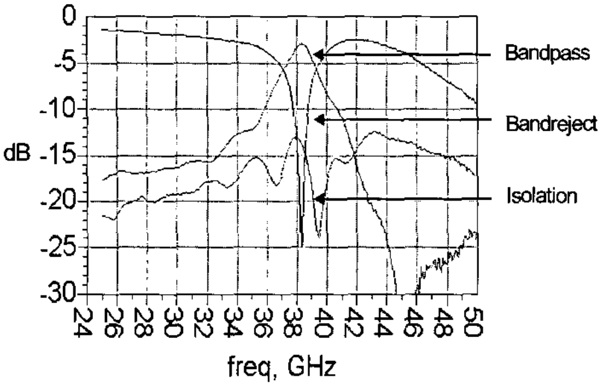

Fig.2 c) Performance of the directional filter

IV. Cross-Shaped Microstrip Antenna

A cross-shaped antenna has been designed for the transmission and reception of signals that cover the band between 59-64 GHz. This antenna can be easily integrated within a wireless millimeter-wave module. Its structure is dual-polarized for the purpose of doubling the data output rate transmitted and received by the antenna. The cross-shaped geometry was utilized to decrease the cross-polarization which contributes to unwanted sidelobes in the radiation pattern [4]. The antenna, shown in Fig.3a, was excited by proximity coupling and had a total thickness of 12 metal layers and 11 substrate layers (each layer was 100 μm thick). There were two substrate layers separating the patch and the feedline, and two substrate layers separating the feedline and the intermediate ground layer. The remaining seven substrate layers contained vias that contributed to the grounding of the structure. The size of the structure was 8mm×7mm. The design was simulated using the TLM-based, 3D full-wave solver MicroStripes 6.0. Fig. 3b shows the scattering parameters versus frequency for this design. The targeted frequency of operation was around 61.5 GHz. The return loss for port 1 was close to -19.5dB @ f_r = 61.35 GHz. The bandwidth for that port/polarization was $\sim$ 6 GHz (58.6-64.6 GHz), while for port 2, the return loss was $\sim$ -28dB @ f_r = 60.07 GHz and the absolute bandwidth was $\sim$ 7.3 GHz (58.45-65.75 GHz). Additionally, there existed a parasitic resonance at 64.24 GHz that has a return loss of $\sim$ -11 dB. The difference in the bandwidth for the two ports can be attributed to the asymmetrical feeding structure between the two ports. For the feed at port 2, the bandwidth achieved by the TM_{10} mode, was hindered by the discontinuity in the feedline, but by adjusting the feed point at the end of the feedline to a different position, a parasitic resonance is brought closer to the TM_{10} resonance. By taking advantage of both resonances, the bandwidth for the feed at port 2 can be slightly wider than the bandwidth achieved for the feed at port 1. The cross-coupling between ports 1 and 2 is below -22 dB for the required bandwidth. Due to the close proximity of the feeding line terminations of port 1 and 2 feedlines, the cross-coupling is hindered, but a value below -22 dB is satisfactory for this application.

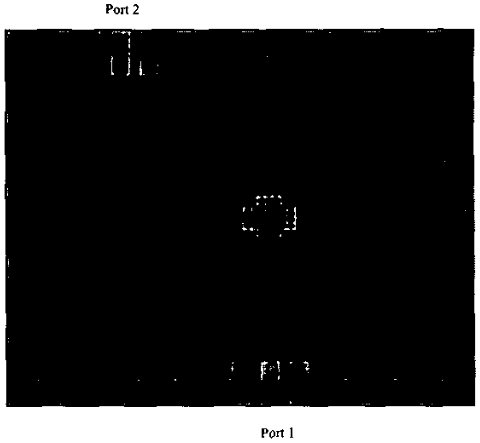

Fig. 3 a) Antenna Structure

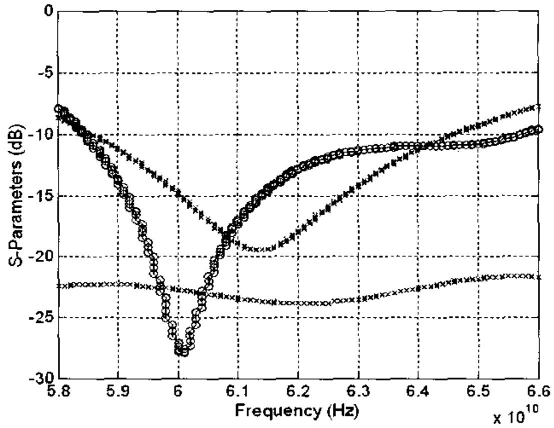

Fig. 3 b) Simulated S-Parameter data versus frequency

V. CONCLUSION

We have presented the development of various advanced 3-D LTCC system-on-package passives' solutions for compact, low-cost wireless front-ends to be used in RF and millimeter-wave frequency ranges. Compact and easy-to-design passive functions, such as filters and antennas, have been demonstrated with excellent performance and high integration potential. The 3D embedded functions which have been developed include patch resonator filters for achieving compactness and great compromise between size and power handling and directional filters to provide easy and compact solutions for applications, such as mixing and multiplexing. The excellent performance of the patch resonator filter is verified through an insertion loss better than 2.3 dB and a return loss larger than 18.2 dB over the pass-band, and a bandwidth of about 6.4%. Also, experimental results of the directional filter show an insertion loss better than 3dB over the band-pass section and a rejection of ~ 25dB at around 38.5GHz over the band rejection section. A double fed cross-shaped microstrip antenna has been designed for the purpose of effectively doubling the data through-put by means of dual polarized wireless channel, covering the band between 59-64 GHz. This antenna can be easily integrated into a wireless millimeter-wave module.

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